

Determining 1^{--} Heavy Hybrid Masses via QCD Sum Rules

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The masses of 1^{--} charmonium and bottomonium hybrids are evaluated in terms of QCD sum rules. We find that the ground state hybrid in charm sector lies in $m_{H_c} = 4.12 \sim 4.79$ GeV, while in bottom sector the hybrid may be situated in $m_{H_b} = 10.24 \sim 11.15$ GeV. Since the numerical result on charmonium hybrid mass is not compatible with the charmonium spectra, including structures newly observed in experiment, we attempt to conclude that such a hybrid does not purely exist, but rather as an admixture with other states, like glueball and regular quarkonium, in experimental observation. However, our result on bottomonium hybrid coincides with the “exotic structure” recently observed at BELLE.

1 Introduction

Quantum chromodynamics (QCD) is believed to be the underlying theory for strong interaction. It is commonly believed that the mechanism responsible for the hadronic properties is subject to the non-perturbative aspect of QCD. Unlike the perturbative QCD which is well understood in some sense, we do not have a reliable and effective way to tackle with the non-perturbative QCD effect yet. In this respect, to get a deep insight in the physics associated with the non-perturbative QCD is one of the most important tasks for the society of high energy physics. So far and in this aim, to evaluate the physical

quantities of hadrons, such as hadron spectra, hadronic transition matrix elements, parton distributions and fragmentation functions, in most cases people have to invoke to typical phenomenology models.

Apart from the so-called regular hadrons, the meson and baryon, QCD also does not exclude exotic hadronic structures, like hybrid, glueball and multiquark structures. Normally, the hybrid meson refers to a state which contains a pair of constituent quarks and a dynamic gluon. In the color-flux tube model, instead, the hybrid corresponds to the structure where the gluonic degree of freedom is excited. Even though these two pictures look different, they may be just two sides of the same object. Thus, whether they are reconcilable with each other or not is an interesting question. Indeed, a careful study may shed light on the hybrid structure and help us to get a better understanding of the non-perturbative QCD effects.

Up to now, a many of effective methods was proposed [1, 2, 3, 4] in evaluating the hybrid mass spectrum, for instance, by studying the quarkonium hadronic transition via multipole expansion [5, 6], the bag model [7], the flux-tube model [8], lattice QCD [9] and QCD Sum Rules [10, 11, 12, 13, 14, 15, 16, 17, 18]. Whereas, those theoretical evaluation results diverse greatly with each other, and hence it is hard to pin down any exotic structures as hybrids in experiment. Therefore, further theoretical investigations are necessary, and they were partially done. For instance, the light hybrid masses evaluated in [19] were updated by Narison and his collaborators [20, 21, 22] in the framework of QCD Sum Rules. Moreover, as indicated in Refs. [23, 24], the hybrid states may not exist independently, but may rather admixtures of hybrids with regular quarkonia or even glueballs with the same quantum numbers. To clarify the messy picture, a more accurate evaluation of pure hybrid spectrum is still vital, namely one can then confront the theoretical predictions with the experimental data to determine the hybrid component of a hadronic state.

Among those theoretical methods in dealing with the non-perturbative effects, QCD Sum Rules innovated by Shifman *et al.*[25] turns out to be a remarkably successful and powerful technique for the computation of hadronic properties. By virtue of QCD Sum Rules, hybrids with various quantum numbers and the flavors have been investigated.

For light-quark hybrids, in order to avoid the mixing between hybrids and ordinary mesons, Ref.[10] considered specifically the hybrids possessing exotic quantum numbers 1^{-+} , and Ref.[11] took another exotic quantum numbers 0^{--} into consideration, and obtained the relative masses and decay amplitudes. Employing the heavy quark effective theory (HQET), Huang, Jin and Zhang evaluated the masses and decay widths of several typical heavy-light hybrids [15]. The heavy-quark hybrids masses were also evaluated in Refs. [16, 17, 18] through QCD Sum Rules.

Recently, a hadronic structure with mass 4324 ± 24 MeV and width 172 ± 33 MeV, has been observed by the BABAR Collaboration in the $\psi(2S)\pi^+\pi^-$ invariant-mass spectrum [26]. This structure is obviously different from $Y(4260)$ reported in Ref.[27]. Later on, two resonant-like structures are observed in also the $\psi(2S)\pi^+\pi^-$ mode by the Belle Collaboration, one resides at $4361 \pm 9 \pm 9$ MeV with a width of $74 \pm 15 \pm 10$ MeV, which coincides with what reported by the BABAR collaboration, and another is at $4664 \pm 11 \pm 5$ MeV with a width of $48 \pm 15 \pm 3$ MeV [28]. A variety of theoretical speculations has been put forward for these hadronic structures. For instance, supposing $Y(4664)$ still be a normal member of the charmonium family, it was interpreted as different charmonium states, like a 5^3S_1 state, a 6^3S_1 state, or even a $5^3S_1 - 4^3D_1$ mixed state [29]. The $Y(4664)$ was also interpreted as a baryonium state [30], the radial excited state of $\frac{1}{\sqrt{2}}(|\Lambda_c \bar{\Lambda}_c\rangle + |\Sigma_c^0 \bar{\Sigma}_c^0\rangle)$, and a $f_0(980)\psi'$ molecule [31]. Starting from the QCD Sum Rules, Albuquerque *et al.* [32] computed the mass of $Y(4664)$ based upon the assumption that it is a vector $c\bar{s}\bar{c}s$ tetraquark state. In the literature, for convenience, $Y(4361)$ and $Y(4664)$ are usually named as $Y(4360)$ and $Y(4660)$, respectively.

Since a series of newly observed “exotic” states in charmonium energy region is 1^{--} hadrons, in this paper we reinvestigate the 1^{--} charmonium hybrid, which is constructed by a pair of charm-anticharm quarks and a gluon, by means of the QCD Sum Rules. In our calculation, the interpolating current of the charmonium hybrid is chosen to be $g_s \bar{\psi} \gamma^\nu \gamma_5 T^a \tilde{G} \psi(x)$, which can be easily found having the correct quantum numbers of the hybrid and was also used in Ref.[16], where, however, the tri-gluon condensate contribution was not taken into account and the plane wave method was used. In our work, we keep the operator product expansion (OPE) to dimension six, the dimension of the tri-gluon

condensate, and take the widely used Fixed-Point gauge technique. Our numerical result indicates that the contribution of the tri-gluon condensate is not negligible and even somehow important for the estimation of the charmonium hybrid mass. In a similar work done by Kisslinger, Parno, and Riordan [18], the current $J_H^\mu(x) = \bar{\Psi}C\gamma_\nu G^{\mu\nu}\Psi(x)$ was employed to calculate the 1^{--} charmonium hybrid, which we think is improper due to the incompatible quantum number with the concerned hybrid, and they obtained a quite low mass of 3.66 GeV.

The rest of this paper is organized as follows. In Sec.II we derive the formulas of the correlation function $\Pi_{\mu\nu}$ in terms of the QCD Sum Rules with the interpolating current for $J^{PC} = 1^{--}$. In Sec III, our numerical evaluations and relevant figures are presented. Section V is remained to summary and concluding remarks.

2 Formalism

In the framework of QCD Sum Rules, the starting point is properly constructing the correlation function, i.e.,

$$\Pi_{\mu\nu}(q) = i \int d^4x e^{iq \cdot x} \langle 0 | T \{ J_\mu(x) J_\nu^\dagger(0) \} | 0 \rangle . \quad (1)$$

Here, the interpolating current J_μ for the heavy hybrid with quantum number $J^{PC} = 1^{--}$ is chosen to be

$$J_\mu(x) = g_s \bar{\psi}^a(x) \gamma^\nu \gamma_5 \frac{\lambda_{ab}^n}{2} \tilde{G}_{\mu\nu}^n(x) \psi^b(x) , \quad (2)$$

where g_s is the strong coupling constant, a and b are color indices, λ^n is the color matrices, and $\tilde{G}_{\mu\nu}^n(x) = \epsilon_{\mu\nu\alpha\beta} G^{n,\alpha\beta}(x)/2$ is the dual field strength of $G_{\mu\nu}^n(x)$. Generally, the two-point function $\Pi_{\mu\nu}$ may contain two distinct parts, the vector part $\Pi_V(q^2)$ and the scalar part $\Pi_S(q^2)$ which represent the contributions of the correlation function to the vector channel $J^{PC} = 1^{--}$ and scalar channel $J^{PC} = 0^{+-}$, respectively. They can be explicitly expressed as

$$\Pi_{\mu\nu}(q) = \left(\frac{q_\mu q_\nu}{q^2} - g_{\mu\nu} \right) \Pi_V(q^2) + \frac{q_\mu q_\nu}{q^2} \Pi_S(q^2) . \quad (3)$$

Since the main task of our work is to study the mass of the vector heavy hybrid with the quantum number 1^{--} , following we only analyze the vector part $\Pi_V(q^2)$.

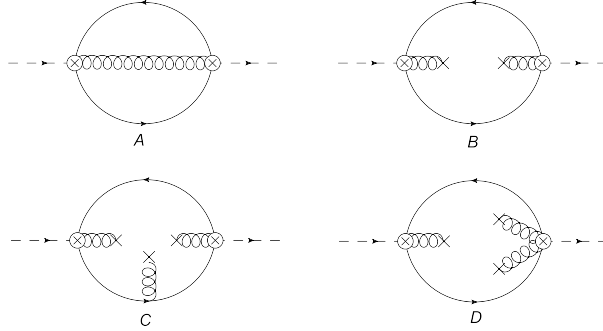


Figure 1: The typical Feynman diagrams for the calculation of heavy vector hybrid mass. Here, the permutation diagrams are implied. Diagram (A) represents for the contribution of unit operator; (B) for the contribution of two-gluon condensate; (C) and (D) for the contribution of three-gluon condensate.

By the operator product expansion (OPE), the correlation function $\Pi_V(q^2)$ can be written as

$$\Pi_V(q^2) = \Pi^{\text{pert}}(q^2) + \Pi_i^{\text{cond}}(q^2), \quad (4)$$

where to satisfy the necessity of our calculation, $\Pi^{\text{pert}}(q^2)$ is obtained by taking the imaginary part of the Feynman diagram A, and $\Pi_i^{\text{cond}}(q^2)$ represents the contributions coming from all possible condensates. In this work, we consider the condensates up to dimension six.

First, we calculate the imaginary part, the absorptive part, of the Feynman diagrams which represents the perturbative contribution to the correlator, and the result reads

$$\begin{aligned} \rho^{\text{pert}}(t) = & -\frac{\alpha_s m_Q^6}{720\pi^2 \sqrt{1-t} t^3} \left[-15t^5 + 185t^4 - 778t^3 - 496t^2 + 1296t - 192 \right. \\ & \left. + 15t^2 \sqrt{1-t} (t^3 - 12t^2 + 48t - 128) \log \frac{\sqrt{1-t} + 1}{\sqrt{t}} \right], \end{aligned} \quad (5)$$

where, $t = 4m_Q^2/s$, and m_Q is the mass of the heavy quark, and $\rho^{\text{pert}}(t) \equiv \text{Im } \Pi(t)$.

The contributions of non-perturbative condensates from diagrams in Figure 1 are

$$\Pi_4^{\text{cond,B}}(q^2) = \int_0^1 dx \frac{\langle g_s^2 G^2 \rangle}{48\pi^2} \{ [8(1-x)xq^2 - 11m_Q^2] + \ln(\Delta)[2(1-x)xq^2 - 3m_Q^2] \}, \quad (6a)$$

$$\Pi_6^{\text{cond,C}}(q^2) = \int_0^1 dx \frac{\langle g_s^3 G^3 \rangle}{192\pi^2} [3x \ln(\Delta) + \frac{2xm_Q^2}{\Delta} + 17x], \quad (6b)$$

$$\begin{aligned} \Pi_6^{\text{cond,D}}(q^2) &= \int_0^1 dx \frac{\langle g_s^3 G^3 \rangle}{384\pi^2} \left\{ 2x(2-3x) \ln(\Delta) - \frac{[2(3-4x)m_Q^2 + x(14x^2 - 27x + 13)q^2]x}{\Delta} \right. \\ &\quad \left. + \frac{(x-1)q^2[3xq^2(x-1)^2 + (2-3x)m_Q^2]x^2}{\Delta^2} + \frac{2(5-24x)x}{3} \right\}. \end{aligned} \quad (6c)$$

Here, $\Delta = -(1-x)xq^2 + m_Q^2$, and symbols B, C, D represent the corresponding diagrams, respectively.

In order to eliminate contributions from higher excited and continuum states, a well-known procedure, the Borel transformation, is performed to above obtained results, and then we get

$$\hat{\mathbf{B}}[\Pi_4^{\text{cond,B}}(q^2)] = \int_0^1 d\omega \int_0^1 dx \frac{\langle g_s^2 G^2 \rangle m_Q^4}{48\pi^2(1-x)x\omega^3} e^{-\frac{m_Q^2}{(1-x)x\omega M_B^2}} (3\omega - 2), \quad (7a)$$

$$\hat{\mathbf{B}}[\Pi_6^{\text{cond,C}}(q^2)] = \int_0^1 d\omega \int_0^1 dx \frac{\langle g_s^3 G^3 \rangle m_Q^2}{192\pi^2(1-x)} \left(2e^{-\frac{m_Q^2}{(1-x)xM_B^2}} - 3\frac{1}{\omega^2} e^{-\frac{m_Q^2}{(1-x)x\omega M_B^2}} \right), \quad (7b)$$

$$\begin{aligned} \hat{\mathbf{B}}[\Pi_6^{\text{cond,D}}(q^2)] &= \int_0^1 d\omega \int_0^1 dx \frac{\langle g_s^3 G^3 \rangle m_Q^2}{384M_B^2\pi^2(x-1)^2x\omega^2} \left\{ -M_B^2(x-1)x \left[e^{-\frac{m_Q^2}{M_B^2(1-x)x\omega}} (6x-4) \right. \right. \\ &\quad \left. \left. + e^{-\frac{m_Q^2}{M_B^2(1-x)x}} (13x-11)\omega^2 \right] + e^{-\frac{m_Q^2}{M_B^2(1-x)x}} (6x-5)\omega^2 m_Q^2 \right\}, \end{aligned} \quad (7c)$$

where, M_B is the Borel parameter.

Suppose the existence of the quark-hadron duality, the resultant sum rule for the mass of the vector heavy hybrid reads

$$m_H = \sqrt{-\frac{R_1}{R_0}} \quad (8)$$

with

$$R_0 = \frac{1}{\pi} \int_{4m_Q^2}^{s_0} \rho^{\text{pert}}(s) e^{-s/M_B^2} + \hat{\mathbf{B}}(\Pi_4^{\text{cond,B}}) + \hat{\mathbf{B}}(\Pi_6^{\text{cond,C}}) + \hat{\mathbf{B}}(\Pi_6^{\text{cond,D}}), \quad (9)$$

$$R_1 = \frac{\partial}{\partial M_B^{-2}} R_0. \quad (10)$$

Here, s_0 is the threshold cutoff introduced to remove the contribution of the higher excited and continuum states [33].

3 Numerical Analysis

For numerical calculation, the leading order strong coupling constant

$$\alpha_s(M_B^2) = \frac{4\pi}{(11 - \frac{2}{3}n_f) \ln(\frac{M_B^2}{\Lambda_{\text{QCD}}^2})} \quad (11)$$

is adopted with $\Lambda_{\text{QCD}} = 0.220 \text{ GeV}$ and n_f being the number of active quarks. Of the two- and three-gluon condensates we take both the prevailing values [33]

$$\langle \alpha_s G^2 \rangle = 0.038 \pm 0.011 \text{ GeV}^4, \quad \langle g_s^3 G^3 \rangle = 0.045 \text{ GeV}^6 \quad (12)$$

and also recently obtained ones [34], i.e.,

$$\langle \alpha_s G^2 \rangle = 0.075 \pm 0.020 \text{ GeV}^4, \quad \langle g_s^3 G^3 \rangle = (8.3 \pm 1.0) \text{ GeV}^2 \langle \alpha_s G^2 \rangle \quad (13)$$

into account. The heavy quark masses are taken to be:

$$m_c = 1.26 \sim 1.47 \text{ GeV}, \quad m_b = 4.22 \sim 4.72 \text{ GeV}. \quad (14)$$

Here, the masses span from the running masses in \overline{MS} scheme to the on-shell masses of QCD Sum Rules [35].

For the selection of an appropriate Borel parameter M_B^2 , we adopt the criteria proposed in Refs.[25, 36, 37]. Defining $m_H(M_B^2)$ in Eq.(8) to be $f_{\text{thcorr}}(M^2)$ while the continuum contribution is absent, i.e., ($s_0 = \infty$), and $m_H(M_B^2)$ to be $m_{\text{H,nopower}}(M_B^2)$ in case of no power corrections. Then we get two discrimination functions $f_{\text{cont}}(M_B^2)$ and $f_{\text{nopower}}(M_B^2)$, satisfying

$$f_{\text{cont}}(M_B^2) = \frac{m_H(M_B^2)}{f_{\text{thcorr}}(M_B^2)}, \quad (15)$$

$$f_{\text{nopower}}(M_B^2) = \frac{m_H(M_B^2)}{m_{\text{H,nopower}}(M_B^2)}. \quad (16)$$

According to the sum rule criteria, the mass function obtained in Eq.(8) is valid only in the situation of M_B^2 being neither too small nor too large. In case M_B^2 is very small, the omitted terms of high-dimensional condensates, which are proportional to high powers of $1/M_B^2$, may become too important to be neglected. To get a reliable prediction of the hybrid mass in QCD Sum Rules, $f_{\text{nopower}}(M_B^2)$ is required to be less than 10% from unit, which ensures the contributions from the non-perturbative condensates to be much less than what from the perturbative term. On the other hand, a very large M_B^2 implies the invalidation of quark-hadron duality approximation. Normally, the $f_{\text{cont}}(M_B^2)$ is required to be 70% more to suppress the contributions of higher resonances and continuum.

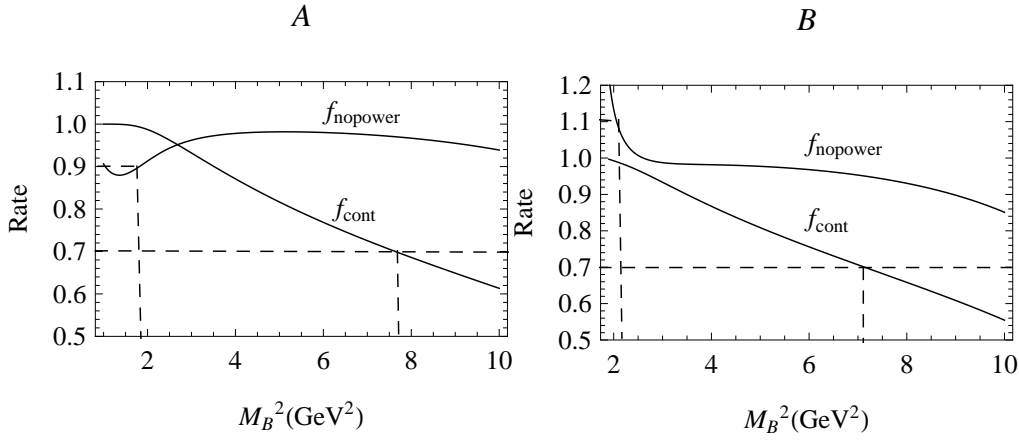


Figure 2: The curves of f_{nopower} and f_{cont} for charmonium hybrid versus Borel parameter M_B^2 while the continuum threshold cutoff $s_0 = 26 \text{ GeV}^2$. Figures A and B correspond to the gluon condensates from [33] and [34], i.e. Eqs.(12) and (13), respectively.

For charmonium hybrid, to find the reliable sum rule for hybrid mass according to the aforementioned criteria, in Fig. 2, we draw the curves of f_{nopower} and f_{cont} as functions of M_B^2 . The figure indicates that f_{nopower} and f_{cont} may satisfy the above mentioned requirements, i.e., the contribution from pole terms is more than 70% and the contribution from condensates is less than 10%, while M_B^2 lies in between 1.80 to 7.80 GeV^2 for Eq.(12) and between 2.10 to 7.20 GeV^2 for Eq.(13), respectively.

For bottomonium hybrid, as shown in figure 3 the reliable range for M_B^2 lies in between 3.00 to 34.00 GeV^2 for Eq.(12) and between 5.00 to 33.00 GeV^2 for Eq.(13), respectively.

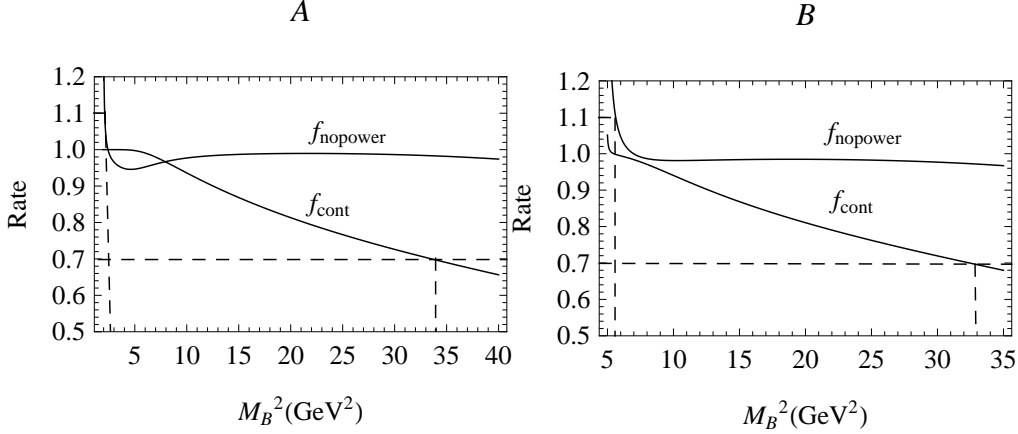


Figure 3: The curves of f_{nopower} and f_{cont} for bottomonium hybrid versus Borel parameter M_B^2 while the continuum threshold cutoff $s_0 = 130 \text{ GeV}^2$. Figures A and B correspond to the gluon condensates from [33] and [34], i.e. Eqs.(12) and (13), respectively.

With the above requirements in establishing the sum rule, to calculate the physical quantities in terms of QCD Sum Rules, one needs to find an optimal window for Borel parameter M_B^2 and threshold parameter s_0 . Within this window, the physical quantities, here the hybrid mass, are maximally independent of the Borel parameter.

In figure 4-A, we draw lines for different threshold parameter s_0 , that is 29, 26, and 23 GeV^2 while Borel parameter varying from 1.80 to 7.80 GeV^2 . The figure evidently indicates that there exists a window for the Borel parameter between 4.20 GeV^2 and 7.80 GeV^2 , in which the evaluated hybrid mass is mostly independent of M_B^2 , especially in case of $s_0 = 26 \text{ GeV}^2$. Namely, it is proper to select the threshold parameter to be 26 GeV^2 , which hints that the mass of the first excited state is above 5.10 GeV . In figure 4-B, the corresponding parameters are $s_0 = 29, 26, 23 \text{ GeV}^2$, $2.50 \text{ GeV}^2 < M_B^2 < 7.20 \text{ GeV}^2$, and the proper threshold parameter is also 26 GeV^2 .

Considering the uncertainties remain in the input parameters, the quark mass, condensates, the Borel parameter M_B^2 and continuum threshold s_0 , we obtain the charmonium hybrid mass to be

$$m_{H_c} = 4.52^{+0.27}_{-0.38} \text{ GeV} . \quad (17)$$

Here, the charm quark mass m_c goes from 1.26 \sim 1.47 GeV ; the condensates take the

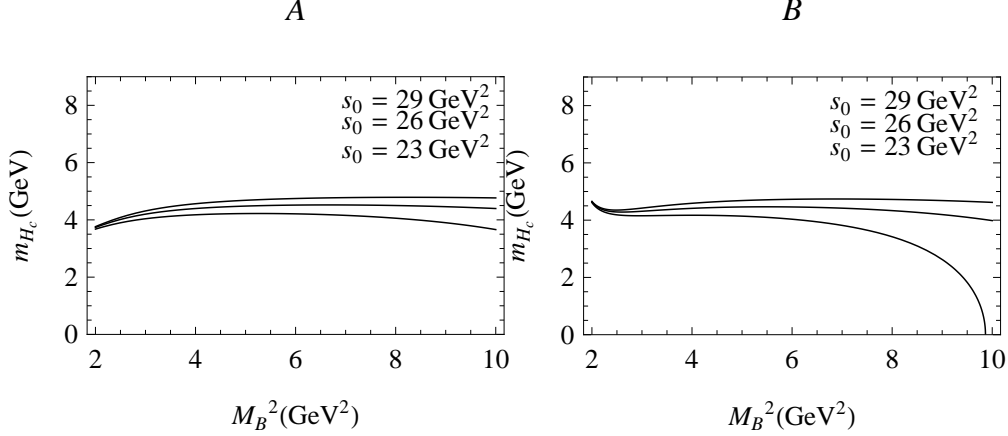


Figure 4: The dependence of 1^{--} charmonium hybrid sum-rule mass on the Borel parameter M_B^2 with different continuum threshold cutoffs s_0 , that is 29 GeV^2 , 26 GeV^2 and 23 GeV^2 from up to down in the figure. Figures A and B correspond to the gluon condensates from [33] and [34], i.e. Eqs.(12) and (13), respectively.

magnitudes of Eq.(12); the Borel parameter M_B^2 varies from 4.20 GeV^2 to 7.80 GeV^2 ; and the continuum threshold s_0 changes from 23 GeV^2 to 29 GeV^2 . The central value of m_{H_c} in Eq.(17) is reached by taking the central values of the quark mass and condensates, while setting $s_0 = 26 \text{ GeV}^2$ and $M_B^2 = 6.00 \text{ GeV}^2$.

For the gluon condensates taken as Eq.(13), we obtain the charmonium hybrid mass to be $m_{H_c} = 4.45^{+0.28}_{-0.32} \text{ GeV}$ with $s_0 = 26 \text{ GeV}^2$ and $M_B^2 = 6.00 \text{ GeV}^2$, which is slightly higher than (17).

In bottomonium sector, by the same procedure, but with inputs $s_0 = 130 \text{ GeV}^2$ and $M_B^2 = 20 \text{ GeV}^2$ as shown in figure 5, we readily obtain the 1^{--} bottomonium hybrid mass, that is $m_{H_b} = 10.81^{+0.23}_{-0.24} \text{ GeV}$ and $10.70^{+0.45}_{-0.46} \text{ GeV}$ for condensates from [33] and [34](Eqs.(12) and (13)), respectively.

4 Summary and Conclusions

In this work we recalculate the 1^{--} heavy quarkonium masses in the framework of QCD Sum Rules. The central part of this calculation relies on the evaluation of the

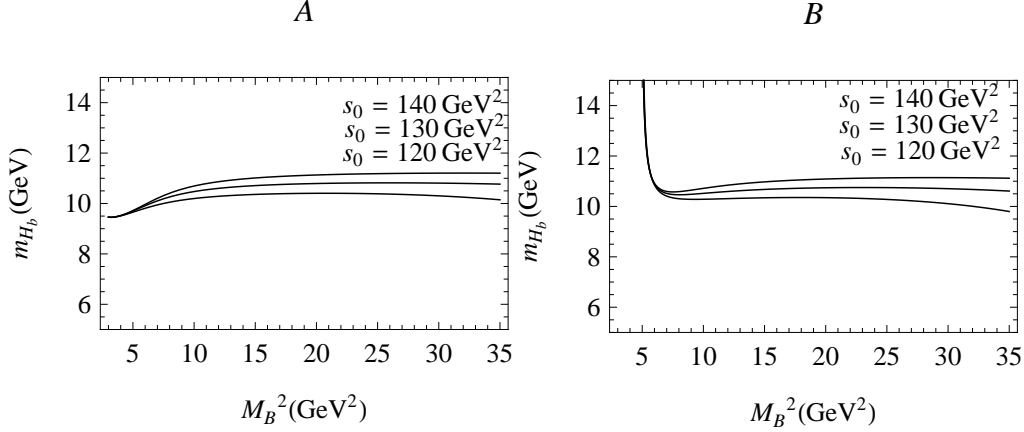


Figure 5: The dependence of 1^{--} bottomonium hybrid sum-rule mass on the Borel parameter M_B^2 with different continuum threshold cutoffs s_0 , that is 140 GeV^2 , 130 GeV^2 and 120 GeV^2 from up to down in the figure. Figures A and B correspond to the gluon condensates from [33] and [34], i.e. Eqs.(12) and (13), respectively.

Wilson coefficients of the operators for the two point correlation function constructed with a suitable hybrid current. In former studies [16, 18], people also fought the same target but with some differences from this work. In previous works, operator expansion only up to dimension four, but in our study the dimension six operators are taken into account. And our results indicate that the dimension six operator, the three-gluon condensate, is important in attaining a wide stable plateau and hence a stable sum rule, which makes the predictions for the masses of $c\bar{c}G$ and $b\bar{b}G$ hybrid states more reliable. We find the interpolating current used in Ref.[18] is improper, and our procedure in establishing the sum rule differs from what performed in Ref.[16]. In our calculation, the central values of charmonium- and bottomonium-hybrid masses are 4.52 GeV and 10.81 GeV for condensates in (12) and 4.45 GeV and 10.70 GeV for condensates in (13), respectively.

Considering of the Y states in charmonium region which are observed recently at the B-factories, since our predicted mass of the charmonium hybrid resides between $Y(4360)$ and $Y(4660)$, we are tempted to conclude that neither of the $Y(4260)$, $Y(4360)$ and $Y(4660)$ states can attribute to pure charmonium hybrid state. If we take the errors into consideration seriously, the masses of $Y(4360)$ and $Y(4660)$ are closer to our estimation, thus might be candidates. However, at present stage it is still hard to draw a definite

conclusion. As a matter of fact, by the discussion given in the introduction, a pure hybrid or glueball might not independently exist. The observed structures could be admixtures of relevant hybrid with glueballs and regular quarkonia with the same quantum numbers [23, 24]. Therefore, in this sense it is understandable why the theoretical hybrid mass does not coincide with any of the resonances observed in experiments. To clarify this issue, i.e., to calculate the mixing angles among states with the same quantum numbers, we need a bigger database on the exotic states, which might be available at the LHCb and planned Super-Flavor factory.

Finally, we have also estimated the mass of 1^{--} bottomonium hybrid state with quite small uncertainties, the $b\bar{b}G$, which is compatible with the recent BELLE observation of the exotic $Y_b(10890)$ [38], and may confront to the LHCb data in near future.

Acknowledgments

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